A Brief History of Early Computational Electromagnetics at The Ohio State University ElectroScience Laboratory

Edward H. Newman, Ohio State University, ElectroScience Laboratory
1320 Kinnear Rd., Columbus, OH 43212, newman@ee.eng.ohio-state.edu

I. Introduction

This paper will survey the history of computational electromagnetics (CEM) at The Ohio State University ElectroScience Laboratory (ESL) prior to 1990. By computational electromagnetics, it is meant a numerical technique in which the unknown currents or fields are expanded in terms of N basis functions, and the unknown coefficients in the expansion are found as the solution of a matrix equation. Prior to 1990, virtually all of the CEM work at the ESL was with the Method of Moments (MM), and thus this article will focus solely on the MM. The reader should understand that with the page limitations imposed, it was impossible to cite all of the significant work in the MM done at the ESL.

II. The 1960's and Before

One of the earliest uses anywhere of the digital computer for the solution of electromagnetic scattering problems was carried out by Edward M. Kennaugh using what he termed the "method of approximate tangential field matching". In his dissertation in 1959 [1], Kennaugh considered the problem of plane wave scattering by perfectly conducting prolate and oblate spheroids along an axis of symmetry. He employed an 8 term multipole expansion of the scattered field. Setting the total tangential electric field to zero at 21 evenly spaced points on the surface resulted in a 21 x 8 system of equations which were solved in a least squares sense for the 8 unknown coefficients in the multipole expansion. The coefficients in the 21 x 8 system of equations were computed on a "desk computer", and were then entered into an IBM 650 computer which solved the equations in about 10 min.

The first person at The ElectroScience Lab to make a career in computational electromagnetics was Jack H. Richmond who, in the early 1960's, began to work on what he called the "linear equation solution". In May of 1965, Richmond published the solution for TM^z scattering by a dielectric cylinder of arbitrary cross section employing the volume current approach [2]. Richmond segmented the cylinder into N nearly square cells over which the electric field could be considered as essentially constant. By enforcing the volume equivalence theorem at the center of each cell, he obtained N simultaneous equations which could be solved for the field (or equivalent polarization current) in each cell. Richmond concluded by stating that solutions with 100 unknowns could be obtained with the IBM 7094 computer. In July of 1965, Richmond published the solution for an array of 2D thin perfectly conducting wires [3]. He showed that scattering by an array of closely spaced wires is very close to that of a solid cylinder, thereby introducing the concept of the wire-grid model

Jack Richmond and Gary A. Thiele were among the early pioneers in the application of the method of moments to finite length thin wires. In the author's view, this was a watershed event in the method of moments, since it provided a tool for the analysis of real antennas, and eventually led to the development of general purpose MM wire codes. In 1965, Richmond published a review article on the "linear -equation solution" method, and applied it to the scattering by thin perfectly conducting wires and dielectric rods [4]. He employed an entire domain Fourier series expansion for the current and point matching weighting in which the boundary conditions were enforced at N discreet points. In 1966, Thiele presented a similar solution, except that he treated a radiating dipole antenna [5]. These works were important in that they permitted an accurate calculation of the wire current without the need for extensive analytical solutions or short wire approximations, and included the effects of the finite wire radius. As a point of time reference, Harrington published his famous Proceeding of the IEEE article on the MM in 1967 [6]. In 1969, Thiele extended his solution for a single dipole to an array of dipoles, and applied the method to the Yagi-Uda array [7]. This was significant because it showed that the MM was able to include the effects of mutual coupling between array elements. Up to that point, mutual coupling between antennas was difficult to compute, and antennas like the Yagi-Uda had to be designed by experimental cut and try

methods. Thiele obtained very good results for comparisons of computations and measurements for Yagi-Uda arrays, thereby demonstrating that numerical techniques in EM could be a practical tool for antenna design. Much of Thiele's early work on wire antennas was summarized in a book chapter [8].

Richmond and Thiele's early wire solutions were based upon entire domain Fourier expansions, and could not be easily extended to more general wire shapes. As a result, Richmond soon began working on his overlapping, piecewise sinusoidal (PWS) dipole, subdomain basis functions. The PWS dipole remains possibly the best expansion/weighting function for thin wires, since it requires fewer unknowns than almost any another combination. It produces a wire current that is continuous (no unphysical point charges) and goes to zero at the wire endpoints. Finally, it is the only finite length current whose fields and mutual impedances can be determined exactly. This allowed the critical self impedance terms in the MM matrix equation to be evaluated with very high precision, and without the need for time consuming numerical integrations. In 1969 Richmond and Don V. Otto published the exact near and far zone fields of a PWS current [9], and in 1970 Richmond and N. Hugh Geary published exact expressions for the mutual impedance between arbitrary skew oriented PWS currents in terms of exponential integrals [10-12].

III. The 1970's

By 1973, Richmond had finished his PWS thin wire code which was based upon the reaction concept developed by Victor H. Rumsey in 1954 [13]. The code was capable of analyzing thin wire antennas or scatterers at complex frequencies in an arbitrary homogeneous medium, including the effects of lumped loads, dielectric shells, and finite wire conductivity. Although Richmond submitted his thin wire formulation for publication in the IEEE Transactions on Antennas and Propagation, it was rejected without review since it exceeded the maximum allowable page limitation, and Richmond never saw the need to shorten and resubmit it. As a result, except for a brief computer program description [14], Richmond's thin wire theory appeared only in ElectroScience Lab reports [15,16], until most of it was included in a 1991 IEEE Press reprint book [17]. Richmond's thin wire code greatly expanded the application and interest in computational electromagnetics since it allowed an antenna engineer, who was not an expert in the MM or EM analysis, to analyze the radiation and scattering from realistic problems by simply entering that geometry into the code. In 1972 Pradeep K. Agrawal, George Richards, G.A. Thiele, and J.H. Richmond employed the PWS thin wire formulation to analyze the TEM line antenna [18], and by 1975 Yau T. Lin and Richmond were constructing wire grid models of aircraft [19].

In 1975 Nan N. Wang made a major advance in the MM by developing the surface patch model [20], which models a solid metallic surface as surface currents. As opposed to the earlier wire grid models, surface patch models are more accurate, and also use far fewer unknowns, resulting in a much more efficient MM solution. In 1978 Edward H. Newman and David M. Pozar solved the problems of rectangular plate/plate and wire/plate junctions [21], and E.H. Newman and Pravitt Tulyathan solved the problem of a wire antenna in the presence of a dielectric or ferrite material body [22]. Combining these with Newman and Tulyanthan's 1982 quadrilateral surface patch solution for polygonal plates [23] formed the basis for the *Electromagnetic Surface Patch Code* (ESP) which can model an arbitrary antenna or scatterer as an interconnection of thin wires, polygonal plates, and polygonal dielectric volumes.

In parallel with the work on the MM, Robert G. Kouyoumjian [24] and others at the ElectroScience Lab were pioneering the development of the Geometrical Theory of Diffraction (GTD). It was thus natural that in 1975 Gary Thiele and Tom H. Newhouse developed the hybrid MM/GTD method for combining the two techniques [25]. In the hybrid MM/GTD method, the MM is used to treat the electrically small part of the problem, while the GTD is used for the electrically large part. The result is an extremely efficient solution which has the potential for treating electrically very large problems. In the same year, a complementary technique for combining the MM and GTD was developed by Walter D. Burnside, Chong L. Yu, Ronald J. Marhefka. In their technique, often referred to as the GTD/MM method, the MM is used to determine the diffraction coefficient from an edge for which no analytical diffraction coefficient is known [26].

IV. The 1980's

For over 30 years Benedikt A. Munk and his students have made major contributions to the Periodic Method of Moments (PMM) analysis of large periodic arrays, and its application to the design of frequency selective surfaces (FSS). Much of this work has appeared only as thesis, dissertations, and ElectroScience Lab reports. In 1974 Edward L. Pelton and Benedikt A. Munk published the design of a

metallic radome using 3 legged slots [27], and in the same year B.A. Munk, Raymond J. Luebbers and Robert D. Fulton analyzed the transmission through a two layer array of loaded slots [28]. In 1975 R.J. Luebbers analyzed a periodic slot array using a mode matching technique [29]. Over the next several years various problems related to the PMM and FSS were attacked by Munk's students Alan J. Fenn [30], Clay J. Larson [31], Erol K. English [32], Tom W. Kornbau [34,35], and Brian M. Kent [36]. In 1984 Lee Henderson developed the PMM solution for arbitrary wires or slots in a stratified medium [37]. This led to the PMM code, still in widespread use for the analysis and design of FSS. In 2000, Munk summarized much of his knowledge and experience related to FSS in a book [38], with another scheduled for the summer of 2003.

In 1983, Richmond, Newman and Bing W. Kwan realized the potential of the MM for analyzing printed circuit antennas, and published solutions for the self and mutual impedance between rectangular microstrip antennas [39]. In an attempt to extend the range of the MM to electrically larger bodies, in 1985 J.H. Richmond developed a technique known as the physical basis MM. In the physical basis MM one build the physics of the problem into the basis functions, so that the number of unknowns is no longer proportional to electrical size. In Richmond's physical basis MM solution for scattering by a thin dielectric strip, he expanded the current in terms of a forced wave plus two surface waves, resulting in a $N = 3$ term MM solution, independent of the width of the strip [40].

V. Conclusions

Beginning with the early work of Kennaugh, Richmond and Thiele, the ElectroScience Lab has made many significant contributions to CEM. The ElectroScience Lab continues to have a strong group in CEM, with the present work focusing on finite element methods (FEM), the finite difference time domain method (FDTD), and "fast" MM techniques.

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